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# A Dust Emission Model for Very Young Galaxies: Expected Properties and Far Infrared Diagnostics

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**Abstract.** Dust plays crucial roles in galaxy formation and evolution. In the early epoch of galaxy evolution dust is only supplied by supernovae (SNe). With the aid of a new physical model of dust production by SNe, we constructed a model of dust emission from forming galaxies. We show the evolution of the spectral energy distribution (SED). Then we adopt this model to a local starbursting dwarf galaxy SBS 0335−052. Further we discuss the SEDs of high redshift galaxies, and consider their observational feasibility.

## 1. Introduction

Active star formation (SF) is followed by heavy element production from the birth and death of stars. Since the produced heavy elements generally exist in the form of dust grains, the dust grains absorb ultraviolet (UV) light and re-emit it in the far infrared (FIR).

Indeed, there is an extreme category of high-$z$ galaxies which have large amount of dust and are extremely luminous in the FIR and submillimeter (submm) wavelengths. Heavily hidden SF is suggested in these galaxies (e.g., Takeuchi et al. 2001a,b). By examining the luminosity functions (LFs) at UV and FIR from *GALEX* and *IRAS*/*Spitzer*, Takeuchi, Buat, & Burgarella (2005) proved that the FIR LF shows much stronger evolution than that of UV, though both evolve very strongly. This indicates that the fraction of hidden SF rapidly increases toward higher redshifts up to $z \sim 1$. There is another important observable closely related to the dust emission from galaxies: the cosmic IR background (CIB). Recently, Takeuchi et al. (2006) constructed the IR spectral energy distribution (SED) of the Local Universe. The energy emitted in the IR is 25–30% of the total energy budget. In contrast, the IR (from near/mid-IR to millimeter) contribution is roughly (or even more than) a half in the CIB spectrum (e.g., Dole et al. 2006). This also suggests a strong evolution of the IR contribution to the cosmic SED in the Universe. Thus, understanding the radiative physics of dust is a fundamental task to have an unbiased view of the cosmic SF history.

In general, the IR observational data are obtained from photometric measurements. Then, estimating the total IR luminosity from fluxes at discrete photometric bands is an essential step to discuss the energy budget released in the UV and FIR. Since Takeuchi et al. (2005a) demonstrated good linear relations between MIR and total IR luminosities for several orders of magnitudes in luminosity, We may expect to have a good estimator, at least with a precision

with a factor of five. However, as well known, this is not a trivial task. Various estimators have been proposed based on *IRAS* bands, including the classical FIR (using 60 and 100 $\mu$m: Helou et al. 1988), Dale et al.'s TIR (60 and 100 $\mu$m: Dale et al. 2001b), and its revised version (25, 60, and 100 $\mu$m: Dale & Helou 2002), and Sanders & Mirabel's IR (all *IRAS* bands: Sanders & Mirabel 1996). Takeuchi et al. (2005a) examined these four estimators using a galaxy sample with known SEDs, and showed that they work well for normal galaxies. However, there are a few categories of galaxies for which the FIR-based ones (the former two) do not give a good estimate. We focus on one of these galaxies, i.e., actively star-forming galaxies, and try to model their SEDs.

Throughout this paper, we use a cosmological parameter set of $(h, \Omega_0, \lambda_0) = (0.7, 0.3, 0.7)$, where $h \equiv H_0/100$ [$\mathrm{km\,s^{-1}Mpc^{-1}}$].

## 2. SED Model for Forming Galaxies

### 2.1. Species and size distribution of dust grains produced by SNe II

Nozawa et al. (2003, hereafter N03) investigated the formation of dust grains in the ejecta of Population III SNe (SNe II and PISNe, whose progenitors are initially metal-free), taking into account the following aspects: (i) the time evolution of gas temperature is calculated by solving the radiative transfer equation including the energy deposition of radioactive elements. (ii) the radial density profile of various metals is properly considered, and (iii) unmixed and uniformly mixed cases in the He core are considered. In the unmixed case, the original onion-like structure of elements is preserved, and in the mixed case, all the elements are uniformly mixed in the helium core. Takeuchi, Buat, & Burgarella (2005) showed that the unmixed dust production is preferred to reproduce the SED of a local starbursting dwarf galaxy SBS 0335−052 (discussed below). In addition, Hirashita et al. (2005) proved that the unmixed scenario can also reproduce the extinction curve of a high-redshift quasar. Hence, in the following, we only discuss the unmixed case. The size of the grains spans a range of three orders of magnitude, depending on the grain species. The size spectrum summed up over all the grain species has a very broad distribution, and very roughly speaking, it might be approximated by a power law.

### 2.2. Star formation, chemical evolution, and dust production

For constructing the chemical evolution model of a young galaxy, we adopt the following assumptions:

1. We use a closed-box model, i.e., we neglect an infall and outflow of gas in the scale of a star-forming region.

2. For the initial mass function (IMF), we adopt the Salpeter IMF (Salpeter 1955): $\phi(m) \propto m^{-2.35}$, with mass range of $(m_\mathrm{l}, m_\mathrm{u}) = (0.1\ M_\odot, 100\ M_\odot)$.

3. We neglect the contribution of SNe Ia and winds from low-mass evolved stars to the formation of dust, because we consider the timescale younger than $10^9$ yr.

4. The interstellar medium is treated as one zone, and the growth of dust grains by accretion is neglected. Within the short timescale considered here, it can be assumed safely.

5. We also neglect the destruction of dust grains within the young age considered (see e.g., Jones, Tielens, & Hollenbach 1996).

6. We assumed a constant SFR for simplicity.

Using these assumptions, we calculate the chemical evolution.

### 2.3. SED construction

In this subsection, we present the construction of the SED from dust. All the details of the calculations are presented in Takeuchi et al. (2003), Takeuchi & Ishii (2004b), and Takeuchi et al. (2005a). (hereafter T03, T04 and T05, respectively).

1. *Stochastic heating of very small grains*

   Very small grains cannot establish thermal equilibrium with the ambient radiation field. This is called stochastic heating. To treat the effect, we applied a multidimensional Debye model (e.g., Draine & Li 2001) to the specific heats of the grain species.

2. *Emission*

   The emission from dust is calculated basically according to Draine & Anderson (1985) (see T03). Total dust emission is obtained as a superposition of the emission from each grain species. We constructed $Q(a, \lambda)$ of each grain species from available experimental data via Mie theory.

3. *Extinction*

   Self-absorption in the MIR for a very optically thick case is treated by a thin shell approximation (see T04).

## 3. Results

### 3.1. Evolution of infrared SED

We first show the evolution of the IR SED of forming galaxies. For these calculation we adopted the star formation rate SFR $= 1\,M_\odot\,\mathrm{yr}^{-1}$. We adopt $r_{\mathrm{SF}} = 30$ pc and 100 pc. These values are relevant when describing 'dwarf-like' young galaxies. The results are presented in Figure 1[1]. We calculated the evolution of the SED in the age range of $10^{6.5}$–$10^8$ yr. After $10^{7.25}$ yr, the N–MIR continuum is extinguished by the self-absorption in the case of $r_{\mathrm{SF}} = 30$ pc. In contrast, the self-absorption is not significant for $r_{\mathrm{SF}} = 100$ pc. The SEDs have their peaks at a wavelength $\lambda \simeq 20$–$30\ \mu$m, which is much shorter than those of dusty giant galaxies at $z = 1$–$3$ detected by SCUBA.

[1] The SED data are available at `http://www.kwasan.kyoto-u.ac.jp/~takeuchi/dust.html`.

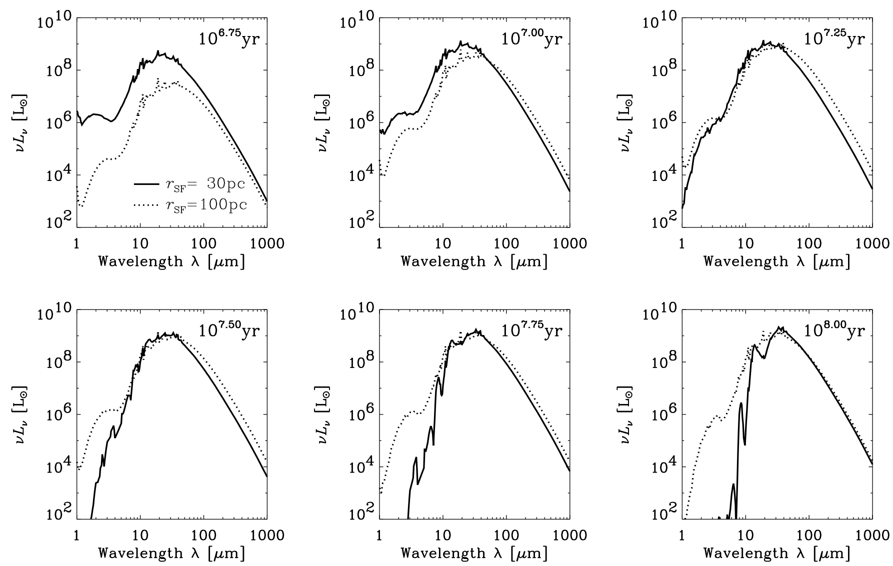


Figure 1. The evolution of the infrared (IR) spectral energy distribution (SED) of a very young galaxy. The sizes of the star forming region, $r_{\rm SF}$, is 30 pc (solid lines) and 100 pc (dotted lines).

## 4. Discussion

### 4.1. Nearby forming dwarf galaxy SBS 0335−052

It is still a difficult task to observe galaxies in their very first phase of the SF, especially to detect their dust emission directly. Since a recent observation of SBS 0335−052 by *Spitzer* has been reported (Houck et al. 2004), it is timely to reconsider these 'textbook objects' with new datasets. In addition, understanding the SEDs of these objects will shed light to the physics of interstellar matter and radiation of high-$z$ galaxies also via empirical studies (e.g., Takeuchi, Yoshikawa, & Ishii 2003; Takeuchi et al. 2005b).

SBS 0335−052 is a local galaxy ($\sim$ 54 Mpc) with SFR $= 1.7\ M_\odot\,{\rm yr}^{-1}$ (Hunt, Vanzi, & Thuan 2001) and extremely low metallicity $Z = 1/41\,Z_\odot$. This galaxy is known to have an unusual IR SED and strong flux at N–MIR. It has a very young starburst (age $\lesssim 5\,$Myr) without significant underlying old stellar population (Vanzi et al. 2000). T03 have modeled the SED of SBS 0335−052 and reported a good agreement with the available observations at that time. However, Houck et al. (2004) presented new data of the MIR SED by *Spitzer*, and reported a deviation of the model by a factor of two or three. Their observation indicated that SBS 0335−052 has even more FIR-deficient SED than ever thought. Hence, it is interesting to examine whether our present model can reproduce the extreme SED of this galaxy.

We show the model SEDs for SBS 0335−052 in Figure 2. We have calculated the SED for $r_{\rm SF} = 10$, 20, and 30 pc. The SFR is fixed to be $1.7\,M_\odot\,{\rm yr}^{-1}$, and the age is $10^{6.5}$ yr. Details of the observational data are found in T03 and T05. In the FIR regime, our model SEDs are consistent with the strong

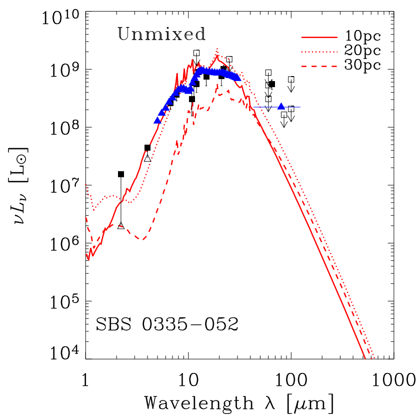


Figure 2. The model for the SED of a nearby star-forming dwarf galaxy SBS 0335−052.

constraint given by Houck et al. (2004). At MIR, though we cannot give an excellent fit to the observed data, the model SEDs roughly agree with them. The very strong N–MIR continuum of SBS 0335−052 is well reproduced. The dust mass calculated by our model at this age of SBS 0335−052 is 1–2 × $10^3$ $M_\odot$, consistent with the observationally estimated value by Dale et al. (2001a). We note that the mass estimation is strongly dependent on the assumed dust species and their emissivities, and grain size distribution. As we discussed in Section 3., the continuum radiation in the N–MIR is dominated by stochastically heated dust emission, which is completely different from modified blackbody. Therefore, when we try to estimate the dust mass, we must take care to determine the corresponding grain properties, i.e., radiative processes and grain which are related to the observed SED of galaxies.

### 4.2. Lyman-break galaxies

Even in LBGs, there is clear evidence that they contain non-negligible amount of dust (e.g., Adelberger & Steidel 2000). A high dust temperature ($\gtrsim 70\,$K) is suggested by subsequent studies (e.g., Ouchi et al. 1999; Chapman et al. 2000; Sawicki 2001). To make a consistent picture of the dust emission from LBGs, we investigate the expected appearance of the LBGs with an improved dust grain formation of N03.

We set the input parameters of the SED model for LBGs as follows. The SFR of LBGs spreads over the range of SFR $\simeq$ 1–300 $M_\odot \mathrm{yr}^{-1}$ with a median of SFR $\simeq 20\, M_\odot \mathrm{yr}^{-1}$ (e.g., Erb et al. 2003). Thus, the basic framework of the T03 model is also valid for LBGs. In this work, we consider the moderate case of SFR $= 30\, M_\odot \mathrm{yr}^{-1}$ over the age of $10^{6.5}$–$10^8$ yr. The most important information to calculate the IR SED is the effective size of the star forming region, but it is the most uncertain quantity (see T04). Since the mean half-light radius of LBGs is estimated to be $\sim 1.6\,$kpc from *HST* observations (Erb et al. 2003), we use the galaxy radius as the radius of a star-forming region, and set $r_{\mathrm{SF}} = 2\,$kpc according to T04.

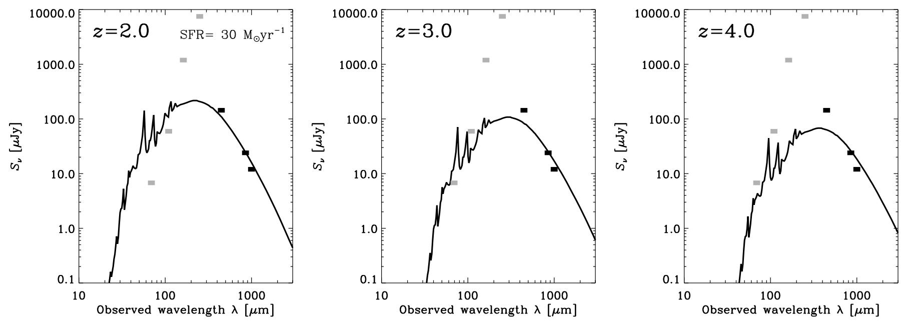


Figure 3. The expected flux densities of an LBG. In this figure we set the galaxy burst age of $t = 10^8$ yr.

We show the observed IR/submm SEDs of LBGs at $z = 2$, 3, and 4 in Figure 3. For simplicity we only show the SED with the age of $10^8$ yr. The thick black short horizontal lines indicate the 3-$\sigma$ detection limits for 8-hour observation by ALMA (Atacama Large Millimeter Array). Here we assumed 64 antennas and three wavelength bands, 450, 850, and 1080 $\mu$m. We also show the 3-$\sigma$ source confusion limit of *Herschel* at 75, 160, 250, and 350 $\mu$m bands by thick gray horizontal lines. These limits are based on 'the photometric criterion' of (Lagache, Dole, & Puget 2003) (see also Takeuchi & Ishii 2004a).

As discussed in T04, the detectability of LBGs is not strongly dependent on their redshifts. Detection at 350 $\mu$m seems impossible for moderate-SFR LBGs. However at longer wavelengths, if the age $\gtrsim 10^8$ yr and SFR $\gtrsim 30\,M_\odot\,\mathrm{yr}^{-1}$, LBGs can be detected at a wide range of redshifts in the submm by ALMA deep survey. In the FIR, *Herschel* will detect the dust emission from LBGs at $z \simeq 2$, but difficult at higher-$z$.

### 4.3. Toward higher redshifts

Based on the above discussions, we give a brief consideration on the observation of very high-$z$ galaxies ($z \gtrsim 5$) here. In modern hierarchical structure formation scenarios, it would be more reasonable to assume a small, subgalactic clump as a first forming galaxy. Consider a dark halo of mass $\sim 10^9\ M_\odot$, then it is expected to contain a gas with mass $\simeq 10^8\ M_\odot$. If gas collapses on the free-fall timescale with an efficiency of $\epsilon_{\mathrm{SF}}$ (we assume $\epsilon_{\mathrm{SF}} = 0.1$), we obtain the following evaluation of the SFR (Hirashita & Hunt 2004):

$$\mathrm{SFR} \simeq 0.1 \left(\frac{\epsilon_{\mathrm{SF}}}{0.1}\right) \left(\frac{M_{\mathrm{gas}}}{10^7\ M_\odot}\right)^{3/2} \left(\frac{r_{\mathrm{SF}}}{100\ \mathrm{pc}}\right)^{-3/2}\ [M_\odot \mathrm{yr}^{-1}]\ . \tag{1}$$

If $M_{\mathrm{gas}} \simeq 10^8\ M_\odot$, we have $\mathrm{SFR} \simeq 3(r_{\mathrm{SF}}/100\ \mathrm{pc})^{-3/2}\ M_\odot\,\mathrm{yr}^{-1}$. In addition, an extremely high-$z$ galaxy observed by *HST* has a very compact morphology (Kneib et al. 2004). We also mention that, from a theoretical side, high-$z$ galaxies are suggested to be dense and compact compared to nearby galaxies (e.g., Hirashita & Ferrara 2002). Thus, we consider a dwarf galaxy with $\mathrm{SFR} = 10\ M_\odot \mathrm{yr}^{-1}$ as an example, and we adopt $r_{\mathrm{SF}} = 30$ pc and 100 pc. The age is set to be $10^7$ yr. If the age is older, they will become easier to detect if

a constant SFR takes place. We show the expected SEDs for such galaxies at $z = 5$, 10, and 20 in Figure 4. As expected, it seems almost impossible to detect such objects by *Herschel* or ALMA.

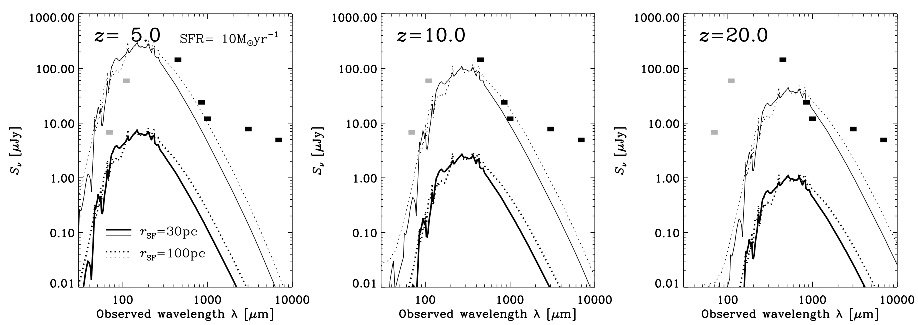


Figure 4. The expected flux densities of a dwarf star-forming galaxy located at $z = 5, 10$, and 20. Solid lines represent the SEDs for $r_{\rm SF} = 30$ pc and dotted lines for $r_{\rm SF} = 100$ pc.

There is, however, a hope to observe such a small forming galactic clump directly: gravitational lensing works very well as a natural huge telescope. If we assume a lens magnification factor of 40, such a small galaxy becomes detectable (thin lines in Figure 4). Since the expected SED of such a compact dwarf galaxy has a strong MIR continuum at their rest frame, it can be feasible to detect at the FIR in the observed frame. A cooled FIR space telescope is more suitable for such observations, and this will be a strong scientific motivation for a future project like *SPICA*. At higher-$z$, they can be detectable by ALMA survey. Even at $z \simeq 20$, they can be detected by a standard 8-hour survey of ALMA, if a lensing takes place. For a practical use, we must estimate how frequently such lensing events occur for high-$z$ objects. Suppose a cluster of galaxies at $z_{\rm l} \simeq 0.1$–$0.2$ whose dynamical mass $M_{\rm dyn}$ is $5 \times 10^{14}\, M_\odot$ and whose mass distribution obeys the singular isothermal sphere. We denote the strong lensing cross section, i.e., the area of the region in the source plane for which the resulting magnification by a cluster is larger than $\mu$, as $\sigma(> \mu)$. Perrotta et al. (2002) presented $\sigma(> \mu)$ as a function of $M_{\rm dyn}$ for $z_{\rm lens} = 1.0$. Since $\sigma(> \mu) \propto {D_{\rm ls}}^2$ ($D_{\rm ls}$ is the angular-diameter distance between the lens and the source), we can convert their result to our condition and obtain $\sigma(> 10) \simeq 30$ arcsec$^2$ on the source plane. This result is almost independent of the source redshifts. Setting the limiting flux density $S_\nu = 1\ \mu$Jy and using the number counts of Hirashita & Ferrara (2002) for galaxies at $z > 5$, we have an expected number of galaxies suffering a strong lensing to be $\simeq 1$–$3$. Thus, we expect at least a few strongly lensed IR galaxies to this survey depth.

## 5. Conclusion

With the aid of a new physical model of dust production by SNe developed by N03, we constructed a model of dust emission from a very young galaxies.

The SED of a local starbursting dwarf galaxy, SBS 0335−052, was calculated. Our present model SED naturally reproduces the strong N–MIR continuum and the lack of cold FIR emission of SBS 0335−052. Then we calculated the evolution of the SED of LBGs. Finally, we considered the observations of forming galaxies at $z \gtrsim 5$. For small forming galaxies with a gas mass $M_{\rm gas} \simeq 10^8\ M_\odot$, it is almost impossible to detect their intrinsic flux by ALMA or *Herschel*. However, the gravitational lensing is found to be a very effective tool to detect such small star-forming galaxies at $z \gtrsim 5$.

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